

# Millennium-scale records of benthic foraminiferal communities from the central Great Barrier Reef reveal spatial differences and temporal consistency

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## ABSTRACT

Understanding long-term community dynamics and the ways in which they respond to major disturbances is a central management theme within coastal marine ecosystems. River outputs from the Queensland coastline directly affect inshore marine communities of the Great Barrier Reef (GBR), Australia. Of these, the Burdekin River exports the highest volume of terrestrial runoff. Following European settlement in the mid-19th century, over three quarters of the native vegetation from the Burdekin catchment were cleared for agricultural purposes. Despite such extensive historical catchment modification, the impact of these changes on the inshore GBR is largely unknown, primarily due to the paucity of long-term ecological data. To assess the effects of modern land-use change on inshore reef environments and to establish an historical baseline of community structure, we examined the sedimentary geochemistry and benthic foraminiferal assemblages of eight sediment cores collected from two coral reefs situated inside (Pandora) and outside (Havannah) an inner-shelf sediment prism formed during the Holocene. Foraminiferal community structure was reconstructed from the past millennium, and the time series was constrained using U-series dating of coral fragments within the cores. Environmental records were reconstructed using stable carbon isotopes ( $\delta^{13}\text{C}$ ) and elemental C:N ratios from bulk sediment samples. Non-parametric analysis of community structure in benthic foraminifers indicated no change in community structure through time at either reef. Despite this apparent ecological persistence through time, significant differences in foraminiferal community structure were observed between the two reefs. The communities were clearly characterized by different functional groups; heterotrophic genera were persistent within, and symbiont-bearing genera were persistent outside, the Holocene inshore sediment wedge. We found no difference in the source of organic matter (interpreted from  $\delta^{13}\text{C}$  values) either between reefs or through time, yet elemental C:N ratios indicated a difference in the amount of organic matter between reefs. The influence of the Holocene inshore sediment wedge was demonstrated by the dissimilarity in sedimentary C:N ratios between the two reefs.

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## 1. Introduction

Historical perspectives provide a frame of reference for understanding modern ecological patterns and processes. Palaeoecology contributes invaluable insight regarding ecological trends across timescales prior to modern environmental pressure (e.g. Greenstein and Pandolfi, 2008; Lybolt et al., 2011; Roff et al., 2012). Landscape modifications are impacting coastal marine systems globally (Pringle, 2001), and runoff of pollutants and nutrients into coastal waters significantly impacts upon the quality of coastal habitats (Fabricius et al., 2005; Sandin et al., 2008). The intensity and cumulative impacts of human activities on the ecological condition of marine communities and their spatial distribution are of growing concern (Halpern et al., 2008). Understanding

how coastal marine communities functioned prior to landscape modification by humans requires a palaeoecological context, which we use here.

Catchments adjacent to the Great Barrier Reef (GBR), Australia, have undergone large-scale land clearing since European settlement in the mid-19th century (Furnas, 2003). The Burdekin River is the second largest catchment adjacent to the GBR, supplying the highest volume of terrestrially-derived sediment into the inshore central GBR (Lewis et al., 2007). The GBR hinterland has undergone major catchment modification since European settlement, with up to 80% of the Burdekin catchment cleared for cattle grazing and substantial modification for horticulture and urban development (Haynes and Michalek-Wagner, 2000; Neil et al., 2002; McCulloch et al., 2003a; Lewis et al., 2007). Previous studies show considerable impacts on the ecology of coral reefs due to enhanced terrestrial runoff (van Woesik and Done, 1997; McCulloch et al., 2003a; Fabricius, 2005). Nevertheless, without an

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understanding of long-term trends in coral reef diversity and function, it is difficult to assess the extent of this anthropogenic footprint.

Weather patterns are known to greatly influence ecosystems and on a global scale have varied notably throughout the past millennium. Such variations in climatic systems call for high-resolution localized proxy records (reviewed in Jones et al., 2009), which are better represented in the Northern Hemisphere compared to the Southern Hemisphere (Jones et al., 2001; Jones and Mann, 2004). Yet, what is known from proxy records suggests there was an increase in La Niña activity during 1520–1660 A.D., followed by a reduction in La Niña intensity and an increase in frequency of El Niño between 1600 and 1780 A.D. (Gergis and Fowler, 2009), which broadly coincides with the Maunder Minimum period of low solar variability 1645–1715 A.D. (Reid, 1997). Additionally, coral Sr/Ca-based SST reconstructions show that the central GBR experienced a cooling period of 0.2–0.3 °C below the long-term average between 1565 and 1700 A.D. but experienced an anomalously warm period between 1700 and 1870 A.D. with similar temperatures to the early 1980s (Hendy et al., 2002). However, the Hendy et al. (2002) record is based on a 5 yr average, and thus can be biased by seasonality change that may affect seasonal difference in coral extension rates. For instance, if the winter-time growth rate during 1565–1700 A.D. was higher than the whole-period mean, then this can create an artifact of cooling due to the fact that the winter-time growth was volumetrically higher than the whole-period mean.

Benthic foraminifers have been successfully used as biological indicators to reconstruct marine conditions and environmental trends (Murray, 1991). This is primarily due to their high taxonomic diversity, prolific abundance, specific ecological requirements, relatively short life cycles (months to years) and because the carbonate tests (exoskeleton) preserve well in the fossil record. The distribution and diversity of modern benthic foraminifers has been studied both for palaeoenvironmental interpretations (Murray, 1991; Sen Gupta, 1999; Murray, 2006) and modern ecological status of disturbed habitats (Narayan and Pandolfi, 2010). Foraminiferal community structure has been used to reconstruct palaeoclimate (Wollenburg et al., 2007), palaeoenvironments (Oldfield et al., 2003), long-term records of eutrophication (Barmawidjaja et al., 1995), modern changes in water quality (Hallock et al., 2003) and sea level (Horton et al., 1999; Edwards and Horton, 2000). Recently, researchers have used the proportion of foraminifers in different functional groups (i.e. opportunistic, heterotrophic and symbiotic) to infer water quality gradients in coral reef and other coastal marine environments (Hallock et al., 2003; Schueth and Frank, 2008; Uthicke and Nobes, 2008; Narayan and Pandolfi, 2010; Uthicke et al., 2010).

Historical water quality can be reconstructed by examining components incorporated into marine sediments (Torgersen et al., 1983; Bird et al., 1995a; Wilson et al., 2005; Lamb et al., 2006; Tsujimoto et al., 2008). Several studies have examined the utility of stable carbon isotopes ( $\delta^{13}\text{C}$ ) along with elementary C:N ratios to reconstruct changes in transported organic matter (Thibodeau et al., 2006; Tsujimoto et al., 2008; Krull et al., 2009). Despite an understanding of the carbon and nitrogen cycle in contemporary coastal zones of the GBR (Alongi and McKinnon, 2005; Fabricius et al., 2005; Cooper et al., 2007), little is known about historical water quality from  $\delta^{13}\text{C}$  and elemental C:N sources. The origin of organic matter in marine sediments, as determined by C:N ratios, is distinguished because of the rich abundance of proteins (Rullkötter, 2006) and the absence of cellulose in marine algae compared to vascular plants (Siegel and Siegel, 1973). The C:N ratio indicates the likely origin of organic matter as either marine (4–10) or terrestrial (>15) (Prah et al., 1980; Wakeham, 2002). Carbon fixation during photosynthesis discriminates against  $^{13}\text{C}$  and depends on the photosynthetic pathway; fractionation in  $\text{C}_4$  pathways (–16‰ to –12‰) differs from  $\text{C}_3$  pathways (–29‰ to –25‰) and again from marine algae (–22‰ to –20‰) (O'Leary, 1988; Meyers, 1994). Historical evidence from elemental and isotopic records allows retrospective studies of past environmental conditions, and therefore provides a

technique to correlate past community structure with long-term water quality trends.

Here we determine the history of benthic foraminiferal communities and terrestrially derived organic matter in reefs adjacent to the Burdekin catchment following European settlement using precisely dated cores extracted from two reefs of the Palm Island region, central GBR (Fig. 1). The main objectives of this study are: (1) to identify and reconstruct the source (e.g. marine or terrestrial) of organic matter from the sediment cores, (2) to determine the historical range of variability in foraminiferal community structure over the past millennium, and (3) to assess the long-term influence of transported organic matter on the taxonomic composition and diversity of benthic foraminiferal communities.

## 2. Methods

### 2.1. Study site and background hydrodynamics

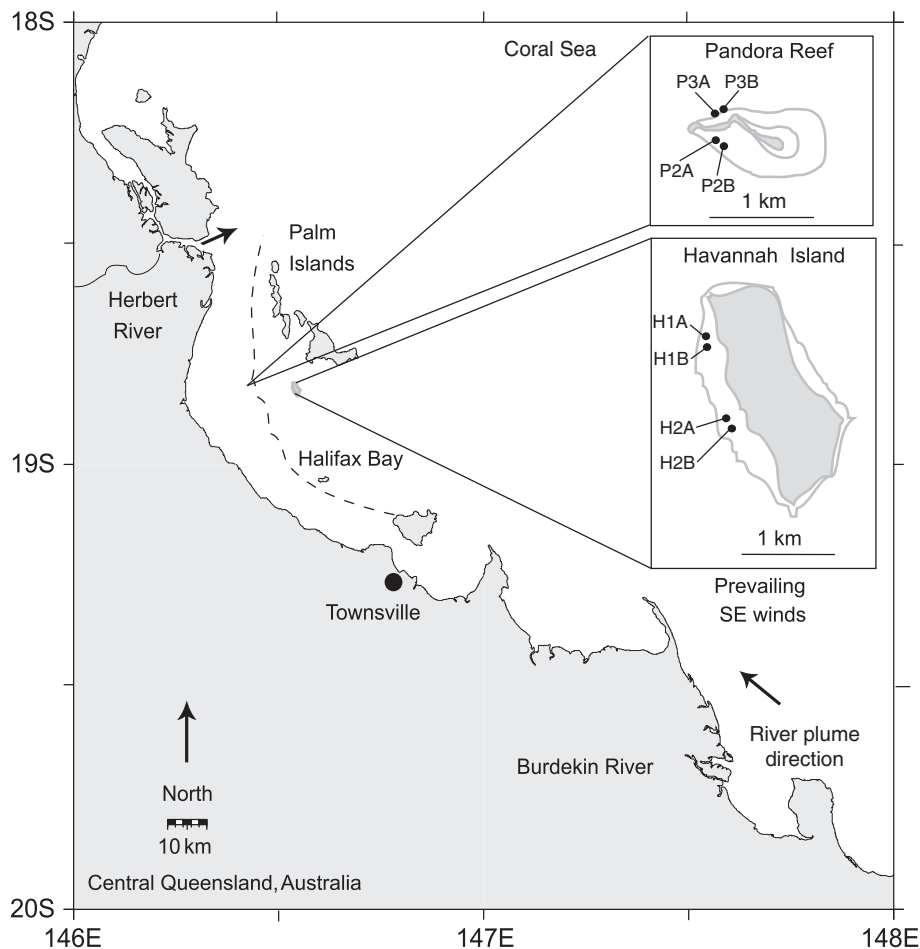
Pandora and Havannah reefs are located in the Palm Islands group of the GBR, ~130 km NW from the mouth of the Burdekin River (Fig. 1). Pandora reef is situated on the boundary of a Holocene inshore sediment wedge (Larcombe and Wolfe, 1999), while Havannah reef is located approximately 10 km seaward (Fig. 1). The Burdekin River is the second largest watershed along the GBR and the single largest contributor of freshwater and sediment to the central GBR shelf. Currents and flood plumes from the Burdekin River can travel on average 200 km north and up to 500 km from the river mouth, and are strongly influenced by south-easterly trade winds and Coriolis forces (Lewis et al., 2006). The river discharge from flooding events affects the inshore reef by decreasing salinity (King et al., 2001), re-suspending and delivering sediment (Fabricius and Wolanski, 2000; Bainbridge et al., 2012), and increasing micronutrients (Lewis et al., 2007).

### 2.2. Field methodology

Sediment coring was conducted at eight localities on the leeward reefs (protected from the prevailing south-easterly swell) of Pandora and Havannah Island (Fig. 1, insert). Using SCUBA, four ca. 2–5 m sediment cores (100 mm diameter aluminum pipe, 1.6 mm wall thickness) were recovered from the reef slope (5 m depth) at each site ( $n = 8$ ). The unconsolidated reef matrices, consisting of coral and molluscan components within a muddy to coarse-grained sand, were extracted using a modified percussion technique (Dardeau et al., 2000). This required several divers, on rotation, to manually operate a slide hammer to force the core through the reef matrix, cap the core and lift it out of the reef. Core recovery of reef matrix was measured by determining penetration depth of the core barrel in the reef and the sediment compaction after extraction. Upon return to the laboratory, cores were longitudinally sectioned into two halves using a circular saw. One half was segmented at 5 cm increments to determine core chronology, and foraminiferal and sediment composition, and the other half archived in a –1 °C freezer. As the accretion rate (as calculated from the core chronology) and length of cores differed, 5 cm sub-samples were selected at 50 yr intervals (as defined by U-series chronology detailed below) to allow temporal replication among cores. Foraminiferal community structure was determined by sieving the sediment from each 5 cm sub-sample through a 125  $\mu\text{m}$  sieve and identifying the first 200 individuals encountered to genus level using descriptions based on Loeblich and Tappan (1994). In 8 out of 112 cases, less than 200 individuals were collected due to the small sediment content in the 5 cm sub-sample.

### 2.3. Thermal ionization mass spectrometry uranium-series dating

Chronologies of each core were established through high-precision uranium-series dating of the coral rubble within the core sections. To



**Fig. 1.** Regional setting of Havannah and Pandora reefs, Palm Islands group, central Great Barrier Reef (GBR), Queensland, and Australia. The main river influence is the Burdekin River with the point of discharge indicated by an arrow (south) and to a lesser degree the Herbert River (north). The direction of these plumes is indicated by arrows. The dashed line is the estimated extent of the Holocene inshore sediment wedge in Halifax Bay (Larcombe and Wolfe, 1999). The inset maps show the location of the sediment cores collected from Pandora (P2A, P2B, P3A and P3B) and Havannah (H1A, H1B, H2A and H2B) reefs. (H)—Hinchinbrook Island.

establish a reliable chronological framework for the cores, 47 representative samples of mainly fast-growing branching coral fragments ( $n=5-8$  per core) were dated using Thermal Ionization Mass Spectrometry (TIMS) outlined in Zhao et al. (2001, 2009) and Clark et al. (2012) in the Radiogenic Isotope Facility at the Centre for Microscopy and Microanalysis (CMM) of the University of Queensland. Where live coral was present on the top layer of the core it was treated as 2008 A.D. (referring to the year when the cores were collected); however, if dead coral was present on the surface an additional U-series age was obtained to constrain the age/depth relationship. Great care is needed for dating samples less than a few hundred years of age by TIMS (see Zhao et al., 2009, for review), with particular attention paid to procedural blank corrections as well as corrections for the contribution of initial/detrital  $^{230}\text{Th}$  which is proportionally much higher than in older samples. Detailed correction procedures are outlined in Zhao et al. (2009), Clark et al. (2012) and Roff et al. (2012). For the initial/detrital  $^{230}\text{Th}$  correction, we adopt a two-component mixing model to calculate the initial  $^{230}\text{Th}/^{232}\text{Th}$  value for each specific sample (see Table S1), rather than applying a commonly used generalized global  $^{230}\text{Th}/^{232}\text{Th}$  initial mean.

#### 2.4. Geochemical analysis

Carbon and nitrogen elemental abundances and carbon-isotope composition were analyzed on a Carlo Erba NCS1500 elemental analyzer (EA) coupled to a Micromass Prism III mass spectrometer (University of Wollongong). To determine total organic carbon ( $C_{\text{org}}$ ) and total nitrogen (N) content,  $\sim 10$  g bulk sediment samples were

freeze-dried, powdered and reacted twice with 10% HCl to remove all calcium carbonate, and washed with deionised water to remove excess HCl. The remaining material was dried for 48 h at 60 °C before loading in  $5 \times 9$  mm tin capsules. Samples were loaded into a 93-well carousel holder. Each analytical run started with eight elemental standards. During the run two elemental standards were analyzed subsequent to every 10 samples. The overall reproducibility of  $\delta^{13}\text{C}$  determinations with this method, including typical sample inhomogeneities and combustion variability is 0.3%. The elemental calibration was carried out with ANU (Australian National University) sucrose (42.11% C;  $-10.47\%$   $\delta^{13}\text{C}$ ), urea (19.98% C; 46.89% N;  $-36.46\%$   $\delta^{13}\text{C}$ ), atropine (70.56% C; 4.84% N;  $-28.53\%$   $\delta^{13}\text{C}$ ), benzoic acid ( $-28.34\%$   $\delta^{13}\text{C}$ ), IAEA-C7 Standard Reference Material (SRM) Oxalic Acid ( $-14.48\%$   $\delta^{13}\text{C}$ ), IAEA-C8 (SRM), Oxalic Acid ( $-18.3\%$   $\delta^{13}\text{C}$ ), and NIST (National Institute of Standards and Technology, SRM) 1547 (45.3% C; 2.88% N;  $-25.88\%$   $\delta^{13}\text{C}$ ).

#### 2.5. Data analysis

##### 2.5.1. Multivariate analyses

We reconstructed benthic foraminifer assemblages using the relative abundance and diversity of genera. Multivariate analyses were conducted to test the effects of sample age and reef site on community structure with the geochemical covariates C:N and  $\delta^{13}\text{C}$  using PRIMER 6.1.10 (Primer-E Ltd, UK) with the PERMANOVA add-on (Anderson et al., 2008). Prior to calculation of a Bray–Curtis similarity matrix, the raw abundance data were square root transformed and

normalized to reduce the influence of genera with high abundance; this transformation increases the weight of rare species in the sample comparisons (Somerfield and Clarke, 1995). Community similarity among all samples was calculated using the Bray–Curtis similarity index (Bray and Curtis, 1957). As the design was unbalanced due to unequal temporal replication, all statistical analyses were calculated using the permutation method in PERMANOVA (a routine for testing the response of one or more variables to a number of factors in an analysis of variance {ANOVA} design), as described in Anderson (2001) and McArdle and Anderson (2001). The assumption of homogeneity of variance was confirmed for both factors using PERMDISP, a distance-based test for homogeneity of multivariate dispersions. Where there was an interaction between one of the factors in the model and a covariate, a linear distance model was run to assess the variance of the predictor variable using the DISTLM function in PERMANOVA. A 2-dimensional non-metric multidimensional scaling (nMDS) ordination was used as a visual representation of the compositional differences among assemblages.

### 2.5.2. Univariate analyses

For each core subsample, the Shannon diversity ( $H'$ ), Pielou evenness ( $J'$ ) and Margalef richness ( $d'$ ) indices were calculated in PRIMER v6 (Clarke and Warwick, 2001). Margalef's index is dependent on sample size and uses species richness; however, the Shannon index assumes individuals are randomly sampled from a community with infinite abundance and therefore applies proportional abundances in the equation. The effects of age and reef upon benthic foraminiferal diversity indices were analyzed using permutation ANOVA. The univariate analysis used the same mixed model structure as the multivariate PERMANOVA, but the resemblance matrix was based on the measurement of Euclidean distance. A full factorial sequential Type I sum of squares model was conducted to test for the effect of the geochemical covariates on each diversity measurement. Where there were no significant effects ( $p > 0.05$ ) and homogeneity of the covariates was confirmed, the covariate was removed and a partial Type III sum of squares mixed model was used. Lastly, spatial and temporal variation in the C:N ratio and  $\delta^{13}\text{C}$  were tested in PRIMER v6 (Clarke and Warwick, 2001) using the Euclidean distance measurement for the resemblance matrix with a univariate ANOVA following the above methods. Where a significant effect was detected, an additional pairwise analysis was conducted to examine the spatial or temporal difference in diversity in greater detail.

### 2.5.3. Geochemical association with foraminiferal community composition

A Mantel test (Mantel, 1967) was used to investigate the relationship between the resemblance matrix of C:N or  $\delta^{13}\text{C}$  and taxonomic similarity in PRIMER using the subroutine RELATE (Somerfield et al., 2002). The sample statistic ( $Rho$ ) was calculated using the Spearman rank correlation between the observed Euclidean distance matrix (either C:N or  $\delta^{13}\text{C}$ ) and the Bray–Curtis similarity matrix. The correlation between the matrices (C:N or  $\delta^{13}\text{C}$  and Bray–Curtis similarity) were permuted 999 times using a randomisation technique, which reorders the values of one matrix with the corresponding values in the second matrix to generate an expected distribution that is compared with  $Rho$  (Sokal and Rohlf, 1995). If the observed measure of  $Rho$  is sufficiently different from the randomized distribution, then an association between the two matrices is accepted.

## 3. Results

### 3.1. TIMS U-series ages

In this study 11 coral genera were used for TIMS U-series dating, the fragments were chosen based on preservation (Table S1). From the TIMS U-series data, the accretion rate was calculated separately for each core.

The linear regressions of stratigraphic position (depth) versus age of each core had an  $r^2 > 88\%$ , implying continuous accretion throughout and a well constrained age–depth correlation. There were only two occurrences of age/depth reversals: one in sample H112BF at 200 cm core depth (~1681 A.D.) and one in sample H27AZ at 45 cm core depth (~1927 A.D.) (Figure S1; Table S1). The cores recovered from Havannah extend from the modern to ~1050 A.D., and those from Pandora, from the modern to ~1200 A.D. Each 5 cm section equates to 4–14 yr of reef matrix growth, with the average section duration being  $11 \pm 3.5$  yr (1-sigma). Additionally, the reef accretion at Pandora and Havannah was comparatively similar throughout the length of the cores (Roff, 2010). For the presentation of all figures and tables, the youngest surface sample was rounded up to 2010; we found this appropriate, as the difference to round was less than the standard error for each section.

### 3.2. Community structure

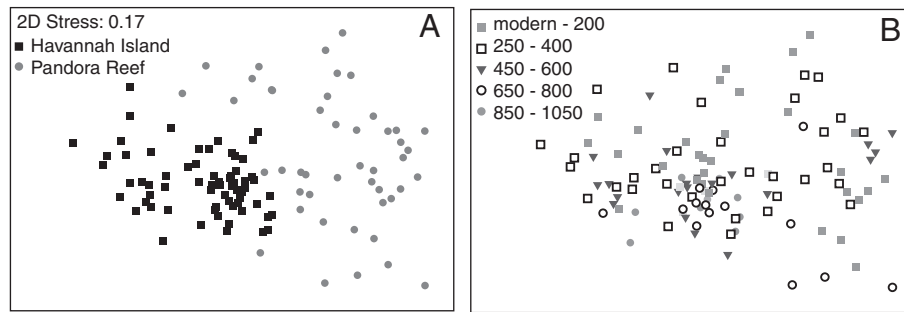
The non-metric multidimensional scaling (nMDS) ordination shows a clear separation in community composition between Pandora and Havannah reefs (Fig. 2A) with no temporal groupings (Fig. 2B). Proportional abundances of the foraminiferal community from each reef did not change significantly through time, yet the communities from the two reefs are significantly different from one another. There are high abundances of heterotrophic individuals from Pandora, whereas communities from Havannah are composed mainly of photosymbiont-bearing individuals (Fig. 3). *Quinqueloculina*, *Eponides* and *Spiroloculina* were the most prevalent heterotrophic genera throughout the cores. *Elphidium* was the most abundant opportunistic genus with several common agglutinated opportunistic genera such as *Sahulina*, *Textularia* and *Clavulina*. *Calcarina*, *Amphistegina* and *Peneroplis* were the most abundant photosymbiont bearing genera (Table S2). The proportions of functional groups (heterotrophic, opportunistic and photosymbiont-bearing) were constant through time at each site and significantly differed between reef sites (Fig. 3). Results from the comparative analysis of Bray–Curtis similarity among foraminiferal communities, indicates no crossed interaction of reef site and the amount of time separating the communities, no temporal difference among communities from the same reef (Fig. 4), and a significant difference in overall similarity between the reefs ( $F_{(1,111)} = 29.256$ ;  $p = 0.001$ ; Table 1).

### 3.3. Diversity

In total 60 genera were identified with a range of 14–38 genera from each sample. Shannon  $H'$  diversity ranged from 2.0 to 2.5 for all samples, Pielou  $J'$  evenness ranged between 0.6 and 0.8 and Margalef  $d'$  richness ranged from 3.0 to 5.0 (Fig. 5). Overall, there were no significant differences in Shannon diversity with respect to reef or age, but a significant difference in Pielou evenness occurred between the two reefs (pseudo  $F_{(1,111)} = 4.947$ ;  $p = 0.025$ ) and a crossed effect of age and reef occurred for Margalef richness (pseudo  $F_{(16,111)} = 2.351$ ;  $p = 0.014$ ; Table 2). Margalef richness differed temporally in <20% of the samples, twice consecutively at 1210 and 1260 A.D. and again in 1460 A.D. (Table S3).

### 3.4. Geochemical analysis

The C:N ratio was consistently lower from the Havannah cores, which were less variable than those from Pandora reef (Fig. 5; Table S4). The average value of C:N from the Havannah cores is within the range of marine-derived organic matter (~10); however, the higher values of C:N from the Pandora cores are typical of terrestrially-derived organic matter (>15). The  $\delta^{13}\text{C}$  values from all cores were within a range of –15 to –10‰, with an average of –12‰ (Fig. 5; Table S4). No significant difference in  $\delta^{13}\text{C}$  values occurred through time or between reefs but a significant interaction occurred between age and reef for C:N ratios (pseudo



**Fig. 2.** Two-dimensional non-metric multidimensional scaling (nMDS) ordination of benthic foraminiferal assemblages derived from sediment cores taken from Havannah and Pandora reefs, inshore GBR. The nMDS ordination is depicted in two ways; samples grouped by (A) reef, and (B) 200 yr time intervals.

$F_{(16,111)} = 2.20$ ,  $p = 0.016$ ; Table 3). Pairwise comparisons showed significantly higher C:N ratios in the sediment from Pandora reef (Table S5). There was no association observed between the  $\delta^{13}\text{C}$  Euclidean distance and the difference in community similarity ( $Rho = 0.06$ ;  $p = 0.11$ ), although communities with greater separation in C:N ratios were less similar in composition ( $Rho = 0.30$ ;  $p = 0.001$ ).

#### 4. Discussion

We present a 1000 yr record of benthic foraminiferal community composition to determine the natural range of variability prior to land use changes following European settlement (mid-19th century). No significant differences in foraminiferal community composition were detected within sites throughout the study period, despite Ba/Ca records indicating peak sediment fluxes during 1968, 1974 and 1981 A.D. (McCulloch et al., 2003a), vegetation clearance and high volumes of cattle throughout the early 1900s (McCulloch et al., 2003b), and climatic variability, such as extreme and protracted ENSO events in the 20th century (Gergis and Fowler, 2009). However, significant spatial differences existed between foraminiferal communities at Havannah and Pandora reefs, and these differences are closely associated with the C:N ratios within the reef sediment.

##### 4.1. Spatial and temporal patterns in foraminiferal communities

Benthic foraminifers inhabit a number of tropical marine ecosystems (Table S2) and assemblages that have the capacity to transform rapidly under changing environmental conditions (Jorissen, 1987; Sen Gupta and Aharon, 1994; Culver and Buzas, 2000; Alve, 2003; Darling et al., 2009). Additionally, the functional traits of foraminifers can be used to characterize organic flux and oxygen availability (van der Zwaan and Jorissen, 1991; Jorissen et al., 1992), salinity (Hottinger, 1983; Hallock and Glenn, 1986), eutrophication gradients within coastal marine waters (Alve, 1995; Culver and Buzas, 1995; Gooday et al., 2009; Narayan and Pandolfi, 2010) and water quality in shallow coral reef environments (Hallock et al., 2003; Schueth and Frank, 2008; Uthicke and Nobes, 2008). We found a predominance of photosymbiont-bearing genera at Havannah reef, and a predominance of heterotrophic genera at Pandora reef (Fig. 3). Differences in the relative abundance of functional traits between the two sites indicate variability in sedimentation, organic matter and light conditions, as observed in modern studies (for example, Hallock et al., 2003; Schueth and Frank, 2008; Uthicke and Nobes, 2008). The heterotrophic assemblages from Pandora reef indicate organic matter enrichment associated with terrestrial

runoff (C:N > 15). The photosymbiont-bearing foraminiferal assemblages from Havannah reef indicate reduced terrestrially derived organic matter (C:N < 10), which could be due to either a lower influence of river runoff or a greater level of mixing with oligotrophic water. Moreover, the foraminiferal communities could also be responding to their position inside or outside the Holocene sediment wedge (Fig. 1; Larcombe and Wolfe, 1999). Pandora reef sits inside the wedge and experiences higher rates of sediment re-suspension, turbidity and terrestrial influence than Havannah reef, which lies ~10 km outside the wedge.

At the generic level, foraminiferal communities from Pandora reef changed slightly after the mid-19th century (Fig. 3B): *Amphistegina* abundance decreased, while *Ammonia* and *Calcarina* increased. Although *Amphistegina* and *Calcarina* are widespread photosymbiont bearing reef-flat genera throughout the Indo-Pacific region (Sen Gupta, 1999), *Calcarina* commonly shows greater flexibility in habitat preference than predicted by its functional grouping (e.g. Renema and Troelstra, 2001). Similarly, *Ammonia* is a known estuarine or brackish water genus (Murray, 1991) and its increase in abundance might indicate a shift in freshwater. These minor increases in *Calcarina* and *Ammonia* abundances from Pandora reef might be connected to the abrupt freshening and cooling of the southwestern Pacific at the end of the Little Ice Age in the late 19th century (Hendy et al., 2002). Additionally, since the 15th century, foraminiferal communities from Havannah reef are observed to decrease in heterotrophic genera and slightly increase in opportunistic and photosymbiont bearing genera but showed no abrupt change in the late 19th century.

Analysis of the diversity of modern benthic foraminifers is not clearly predicted by environmental conditions. For example, highly diverse foraminiferal communities have been found to occupy both fluvial influenced embayments (Narayan and Pandolfi, 2010) and oligotrophic reef environments (Langer and Lipps, 2003). In our study, we observed no differences in Shannon diversity ( $H'$ ), but significantly greater Pielou evenness ( $J'$ ) at Havannah than Pandora reef and a mixed spatial and temporal response of Margalef richness ( $d'$ ). The indices show more variability from Pandora than Havannah reef and may imply some differences in environmental stability between the two sites. Thus, benthic foraminiferal diversity alone is a poor indicator of environmental conditions at our two study sites. Only evenness varies between the reef sites. Among other studies of coral reef organisms, long-term patterns in species diversity have also been observed to persist in the presence of significant environmental fluctuations (Pandolfi, 1996; Tager et al., 2010; Reymond et al., 2011). Overall,

**Fig. 3.** Core profiles of the relative abundance of benthic foraminiferal assemblages from Havannah and Pandora reefs, GBR. Shown are relative pooled abundance (sum is to 100%) of heterotrophic, opportunistic and symbiont-bearing genera from (A) Havannah reef and (B) Pandora reef. All heterotrophic genera contributing less than 5% to the overall community were designated as 'other'. Columns illustrate the relative proportional abundance of the genera contributing to each of the functional groups, with the vertical axis expressed as  $^{230}\text{Th}$  age in calendar years (A.D.).



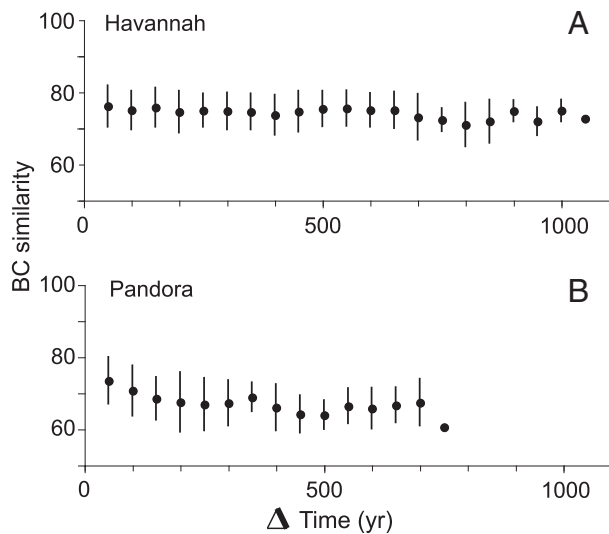


Fig. 4. Average Bray–Curtis (BC) similarity between communities plotted against the length of time separating the communities ( $\pm$  SE) from (A) Havannah reef, and (B) Pandora reef.

the natural range of foraminiferal community composition shows some minor variation but principally temporal consistency as evident from the high community similarity through time regardless of the length of time separating the communities (Fig. 4). This implies that heterotrophic foraminiferal communities within the Holocene inshore sediment wedge were able to withstand 5–10 fold sedimentation increases since large-scale catchment modification. Similarly, the temporal consistency in the species composition and diversity of symbiont-bearing foraminiferal communities from Havannah suggests recent fluvial runoff has not altered the water quality outside the Halifax Holocene inshore sediment wedge sufficiently to affect the ecological structure of foraminiferal communities.

#### 4.2. Evidence from elemental and isotopic markers

Elemental C:N and isotopic  $\delta^{13}\text{C}$  were used to distinguish the origin of organic matter within the ancient sedimentary deposits (Wilson et al., 2005). The C:N ratio from sediment can be used to differentiate the marine vs. terrestrial origin of organic matter (Prahil et al., 1980; Wakeham, 2002). The C:N ratio for marine algae ranges between 4 and 10 (Meyers, 1994), while for terrestrial organic matter the C:N ratio is generally above 15 (Prahil et al., 1980; Wakeham, 2002). Sediment samples from the Havannah cores have a C:N ratio comparable with that of marine algae, likely reflecting phytoplankton blooms with terrestrial and oceanic mixing that occurs during flooding events (Devlin et al., 2001; Devlin and Brodie, 2005). Even though there is a decreasing trend in C:N ratio progressively from the younger sediment of the Pandora cores, the C:N ratio still remains on average  $>15$ , implying a strong influence from terrestrially derived  $\text{C}_4$  vascular plants. When comparing the two reef communities, assemblages appear to be structured according to the C:N ratio. Pandora reef on average has a higher C:N ratio and greater abundance of heterotrophic foraminifers, in contrast to Havannah reef which has a lower C:N ratio and a higher abundance of photosymbiont-bearing foraminifers, indicating clear oligotrophic waters. Thus, benthic foraminifer composition and abundance in coastal marine habitats of the GBR are closely associated with hydrodynamic flux in organic matter.

The fraction of terrestrial organic carbon in marine sediment commonly varies with the distance from a river mouth and the source of organic material (Sackett and Thompson, 1963; Shultz and Calder,

Table 1

A two-factor (age and reef) PERMANOVA model with partial (type III) sums of squares comparing the Bray–Curtis similarity in taxonomic composition of foraminiferal communities from Havannah and Pandora reef. Significance is indicated in bold when  $p < 0.05$ .

Variable	Effect	df	SS	MS	Pseudo-F	<i>p</i>
Bray–Curtis similarity	Age	21	13342	635	1.147	0.207
	Reef	1	16205	16205	29.256	<b>0.001</b>
	Age $\times$ reef	16	8929	558	1.068	0.312

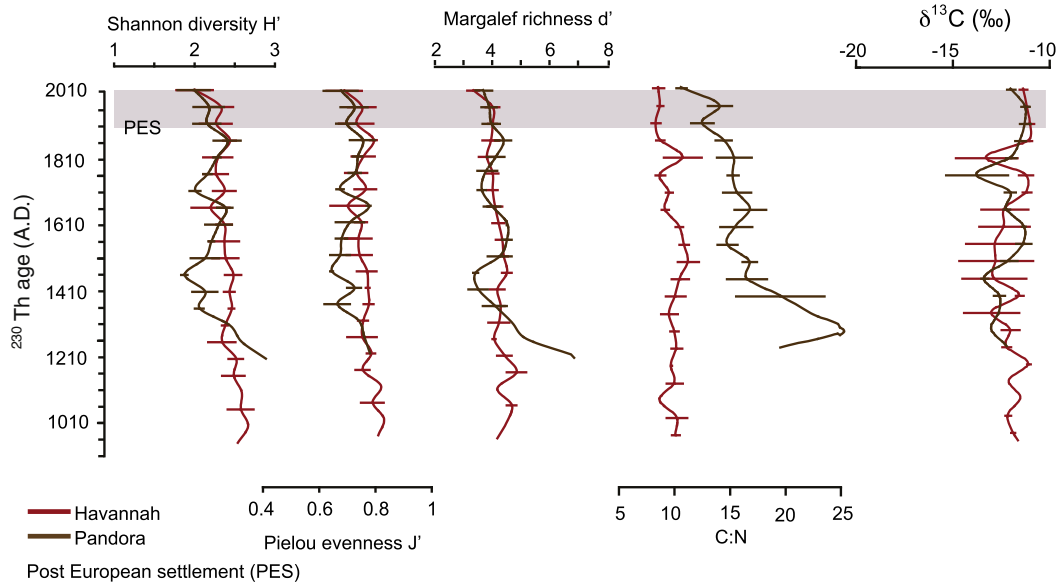
1976; Schwartz et al., 1986; Bird et al., 1992, 1994). Similarly, from the geochemical marker, pentacyclic triterpenoid alcohol (PTA), trace organic compounds from terrestrial plants reach the inner GBR after flood events, with the bulk of terrestrial organic matter restricted to the inshore sediment (Currie and Johns, 1989). The mean  $\delta^{13}\text{C}$  value of local marine organic carbon on the GBR is about  $-19\%$  (Torgersen et al., 1983). To the north of our study site, the bays adjoining Hinchinbrook Island (Fig. 1) display modern sediment with  $\delta^{13}\text{C}$  values between  $-20$  and  $-24\%$  (Torgersen and Chivas, 1985) and are strongly determined by  $\text{C}_3$  mangrove vegetation and sedimentation. These modern studies indicate lower  $\delta^{13}\text{C}$  values than the historic ranges in sediments from Havannah and Pandora reefs ( $-15$  to  $-10\%$ ). Minor variation in the range of  $\delta^{13}\text{C}$  could be attributed to energy-related sorting, deposition, oxidation and mixing between autochthonous and allochthonous sources (Smith et al., 2008), or water deficit during plant growth (Merchant et al., 2010). However, the major discrepancy between the values we observed is most likely due to the source of primary productivity and organic burial.

The  $\delta^{13}\text{C}$  values of organic sediment from Pandora and Havannah reefs are best explained by their location in the path of the modern sediment plume that emanates from the Burdekin River. The  $\delta^{13}\text{C}$  values measured from Havannah and Pandora reef indicate the continuous influence of organic terrestrial sources from a dominant  $\text{C}_4$  metabolic pathway, which have a typical  $\delta^{13}\text{C}$  value of  $-12\%$ . This is indicative of native grasses and introduced sugar cane, which is currently the main crop along the Queensland coast since land clearing post European settlement. It also suggests the predominance of native grasses before cropping. Because both vegetation types have the same metabolic pathway we cannot differentiate the changes in land use from this marker alone. Even though our study found no change in  $\delta^{13}\text{C}$ , Bird et al. (1995b) found a 2% increase in the  $\delta^{13}\text{C}$  values of alkanes extracted from marine sediment in the GBR following land clearing for sugar cane and pasture in the late 1880s along the Johnstone River (about 150 km north of this study site). Despite apparent historical increases in sediment flux (McCulloch et al., 2003a, 2003b), our geochemical analysis from bulk sediments indicate that the composition of transported organic matter has remained constant throughout the last millennium. The long-term history of terrestrial runoff entering the inshore marine waters has shaped the foraminiferal communities at Pandora and Havannah reef before recent catchment modification as evident from the high community similarity through time regardless of the length of time separating the communities.

#### 5. Conclusions

Our analysis of benthic foraminiferal assemblages and their temporal distribution in Pandora and Havannah reefs indicates:

- (1) Site variability was greater than temporal variability among foraminiferal communities over the past 1000 yr. There are no significant signs of community shifts since European settlement or during past climatic fluctuations. Community similarity through time remained constant regardless of the length of time separating the communities.



**Fig. 5.** Core profiles of three biodiversity indices, Shannon diversity ( $H'$ ), Pielou evenness ( $J'$ ), and Margalef richness ( $d'$ ), and two geochemical markers, C:N and  $\delta^{13}C$  ( $\pm$  SE). The vertical axis is expressed as  $^{230}Th$  age in calendar years (A.D.). Shaded area highlights post-European settlement (PES).

- (2) Diversity was relatively high at both reef sites regardless of the functional groups represented or geochemical signature; however, community evenness was greater with a reduction in terrestrial influence, as evident from the C:N ratios.
- (3) Community structure was correlated with spatial changes in the C:N ratios from the core sediment. The relative abundance of the functional assemblages was influenced by the amount of sedimentary organic matter; where a greater abundance of heterotrophic foraminifers were present there was a higher influence of terrestrial runoff, causing lower light conditions and higher amounts of organic matter. A high abundance of photosymbiont-bearing foraminifers occurred in water with a lower influence of organic matter from terrestrial runoff. At our study sites, the threshold between photosymbiont-bearing and heterotrophic foraminifers communities occurred between C:N of 10–15.
- (4) Overall, the natural range of foraminiferal diversity and taxonomic composition showed temporal consistency, which implies these communities were able to withstand 5–10 fold sedimentation increases since large-scale catchment modification.

**Table 2**

Univariate analysis based on the Euclidean distance of Shannon's diversity ( $H'$ ), Pielou evenness ( $J'$ ) and Margalef richness ( $d'$ ) using a PERMANOVA two-factor (age and reef) model with partial (type III) sums of squares for Pandora and Havannah Reefs. Significance is indicated in bold when  $p < 0.05$ .

Variable	Effect	df	SS	MS	Pseudo-F	<i>p</i>
Diversity ( $H'$ )	Age	21	1.935	0.092	1.127	0.338
	Reef	1	0.226	0.226	2.758	0.091
	Age $\times$ reef	16	1.065	0.067	0.814	0.685
Evenness ( $J'$ )	Age	21	0.072	0.003	0.570	0.925
	Reef	1	0.030	0.030	4.947	<b>0.025</b>
	Age $\times$ reef	16	0.055	0.003	0.567	0.892
Richness ( $d'$ )	Age	21	28.205	1.343	3.611	<b>0.001</b>
	Reef	1	0.515	0.515	1.386	0.215
	Age $\times$ reef	16	13.996	0.875	2.351	<b>0.014</b>

**Table 3**

Univariate analysis based on Euclidean distance of the  $\delta^{13}C$  and C:N ratio using a PERMANOVA two-factor (age and reef) model with partial (type III) sums of squares for Pandora and Havannah Reefs. Significance is indicated in bold when  $p < 0.05$ .

Variable	Effect	df	SS	MS	Pseudo-F	<i>p</i>
$\delta^{13}C$	Age	21	78.92	3.76	1.38	0.196
	Reef	1	0.23	0.23	0.08	0.78
	Age $\times$ reef	16	30.07	1.88	0.69	0.77
C:N	Age	21	309.69	14.75	2.85	<b>0.001</b>
	Reef	1	1040.1	1040.1	200.78	<b>0.001</b>
	Age $\times$ reef	16	182.39	11.40	2.20	<b>0.016</b>

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.palaeo.2013.01.001>.

## References

- Alongi, D.M., McKinnon, A.D., 2005. The cycling and fate of terrestrially-derived sediments and nutrients in the coastal zone of the Great Barrier Reef shelf. *Marine Pollution Bulletin* 51, 239–252.
- Alve, E., 1995. Benthic foraminiferal responses to estuarine pollution: a review. *Journal of Foraminiferal Research* 25, 190–203.
- Alve, E., 2003. A common opportunistic foraminiferal species as an indicator of rapidly changing conditions in a range of environments. *Estuarine, Coastal and Shelf Science* 57, 501–514.



- Anderson, M.J., 2001. A new method for non-parametric multivariate analysis of variance. *Austral Ecology* 26, 32–46.
- Anderson, M.J., Gorley, R.N., Clarke, K.R., 2008. PERMANOVA+ for PRIMER: guide to software and statistical methods. PRIMER-E Plymouth Marine Laboratory, Plymouth, UK, p. 214.
- Bainbridge, Z.T., Wolanski, E., Álvarez-Romero, J.G., Lewis, S.E., 2012. Fine sediment and nutrient dynamics related to particle size and flocculation in a Burdekin River flood plume, Australia. *Marine Pollution Bulletin* <http://dx.doi.org/10.1016/j.marpolbul.2012.01.043>.
- Barmawidjaja, D.M., van der Zwaan, G.J., Jorissen, F.J., Puskaric, S., 1995. 150 years of eutrophication in the northern Adriatic Sea: evidence from a benthic foraminiferal record. *Marine Geology* 122, 367–384.
- Bird, M.I., Fyfe, W.S., Pinheiro-Dick, D., Chivas, A.R., 1992. Carbon isotope indicators of catchment vegetation in the Brazilian Amazon. *Global Biogeochemical Cycles* 6, 293–306.
- Bird, M.I., Giresse, P., Chivas, A.R., 1994. Effect of forest and savanna vegetation on the carbon-isotope composition of sediments from the Sanaga River, Cameroon. *Limnology and Oceanography* 39, 1845–1854.
- Bird, M.I., Chivas, A.R., Brunskill, G.J., 1995a. Carbon-isotope composition of sediment from the Gulf of Papua. *Geo-Marine Letters* 15, 153–159.
- Bird, M.I., Summons, R.E., Gagan, M.K., Roksandic, Z., Dowling, L., Head, J., Keith Fifield, L., Cresswell, R.G., Johnson, D.P., 1995b. Terrestrial vegetation change inferred from n-alkane  $\delta^{13}\text{C}$  analysis in the marine environment. *Geochimica et Cosmochimica Acta* 59, 2853–2857.
- Bray, J.R., Curtis, J.T., 1957. An ordination of the upland forest communities of southern Wisconsin. *Ecological Monographs* 27, 326–349.
- Clark, T.R., Zhao, J.X., Feng, Y.X., Done, T., Jupiter, S., Lough, J.M., Pandolfi, J.M., 2012. Spatial variability of initial  $^{230}\text{Th}/^{232}\text{Th}$  in modern *Porites* from the inshore region of the Great Barrier Reef. *Geochimica et Cosmochimica Acta* 78, 99–118.
- Clarke, K.R., Warwick, R.M., 2001. Change in marine communities: an approach to statistical analysis and interpretation, 2nd ed. PRIMER-E Plymouth Marine Laboratory, Plymouth, UK, p. 144.
- Cooper, T.F., Uthicke, S., Humphrey, C., Fabricius, K.E., 2007. Gradients in water column nutrients, sediment parameters, irradiance and coral reef development in the Whitsunday Region, central Great Barrier Reef. *Estuarine, Coastal and Shelf Science* 74, 458–470.
- Culver, S.J., Buzas, M.A., 1995. The effects of anthropogenic habitat disturbance, habitat destruction, and global warming on shallow marine benthic Foraminifera. *Journal of Foraminiferal Research* 25, 204–211.
- Culver, S.J., Buzas, M.A., 2000. Global latitudinal species diversity gradient in deep-sea benthic foraminifera. *Deep Sea Research* 47, 259–275.
- Currie, B.R., Johns, R.B., 1989. An organic geochemical analysis of terrestrial biomarkers in a transect of the Great Barrier Reef Lagoon. *Marine and Freshwater Research* 40, 275–284.
- Dardeau, M.R., Aronson, R., Precht, W.F., Macintyre, P., 2000. Use of a hand-operated, open-barrel corer to sample uncemented Holocene coral reefs. In: Hallock, P., French, L. (Eds.), *Diving for Science in the 21st Century: 20th annual symposium of the American Academy of Underwater Sciences*, St. Pete beach, Florida, pp. 6–9.
- Darling, K.F., Thomas, E., Kasemann, S.A., Seears, H.A., Smart, C.W., Wade, C.M., 2009. Surviving mass extinction by bridging the benthic/planktonic divide. *Proceedings of the National Academy of Sciences of the United States of America* 106, 12629–12633.
- Devlin, M.J., Brodie, J., 2005. Terrestrial discharge into the Great Barrier Reef Lagoon: nutrient behavior in coastal waters. *Marine Pollution Bulletin* 51, 9–22.
- Devlin, M.J., Waterhouse, J., Taylor, J., Brodie, J.M., 2001. Flood Plumes in the Great Barrier Reef: Spatial and Temporal Patterns in Composition and Distribution. Great Barrier Reef Marine Park Authority, research publication 68 Townsville, Australia, p. 113.
- Edwards, R.J., Horton, B.P., 2000. Reconstructing relative sea-level change using UK salt-marsh foraminifera. *Marine Geology* 169, 41–56.
- Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Marine Pollution Bulletin* 50, 125–146.
- Fabricius, K.E., Wolanski, E., 2000. Rapid smothering of coral reef organisms by muddy marine snow. *Estuarine, Coastal and Shelf Science* 50, 115–120.
- Fabricius, K., De'ath, G., McCook, L., Turak, E., Williams, D.M., 2005. Changes in algal, coral and fish assemblages along water quality gradients on the inshore Great Barrier Reef. *Marine Pollution Bulletin* 51, 384–398.
- Furnas, M.J., 2003. Catchments and corals: Terrestrial runoff to the Great Barrier Reef. Australian Institute of Marine Science & CRC Reef Research Centre, Townsville, p. 334.
- Gergis, J.L., Fowler, A.M., 2009. A history of ENSO events since A.D. 1525: implications for future climate change. *Climatic Change* 92, 343–387.
- Goody, A.J., Jorissen, F., Levin, L.A., Middelburg, J.J., Naqvi, S.W.A., Rabalais, N.N., Scranton, M., Zhang, J., 2009. Historical records of coastal eutrophication-induced hypoxia. *Biogeosciences* 6, 1707–1745.
- Greenstein, B.J., Pandolfi, J.M., 2008. Escaping the heat: Range shifts of reef coral taxa in coastal Western Australia. *Global Change Biology* 14, 513–528.
- Hallock, P., Glenn, E.C., 1986. Larger Foraminifera: A tool for paleoenvironmental analysis of Cenozoic carbonate depositional facies. *Palaios* 1, 55–64.
- Hallock, P., Lidz, B.H., Cockey-Burkhard, E.M., Donnelly, D.K., 2003. Foraminifera as bioindicators in coral reef assessment and monitoring: The FORAM index. *Environmental Monitoring and Assessment* 81, 221–238.
- Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., 2008. A global map of human impact on marine ecosystems. *Science* 319, 948–952.
- Haynes, D., Michalek-Wagner, K., 2000. Water quality in the Great Barrier Reef World Heritage Area: Past perspectives, current issues and new research directions. *Marine Pollution Bulletin* 41, 428–434.
- Hendy, E.J., Gagan, M.K., Alibert, C.A., McCulloch, M.T., Lough, J.M., Isdale, P.J., 2002. Abrupt decrease in tropical Pacific sea surface salinity at end of Little Ice Age. *Science* 295, 1511–1514.
- Horton, B.P., Edwards, R.J., Lloyd, J.M., 1999. UK intertidal foraminiferal distributions: implications for sea-level studies. *Marine Micropaleontology* 36, 205–223.
- Hottinger, L., 1983. Processes determining the distribution of larger Foraminifera in space and time. *Utrecht Micropaleontological Bulletin* 30, 239–253.
- Jones, P.D., Mann, M.E., 2004. Climate over past millennia. *Reviews of Geophysics* 42, RG2002 <http://dx.doi.org/10.1029/2003RG000143>.
- Jones, P.D., Osborn, T.J., Briffa, K.R., 2001. The evolution of climate over the last millennium. *Science* 292, 662–667.
- Jones, P.D., Briffa, K.R., Osborn, T.J., Lough, J.M., van Omman, T.D., Vinther, B.M., Luterbacher, J., Wahl, E.R., Zwiwers, F.W., Mann, M.E., Schmidt, G.A., Ammann, C.M., Buckley, B.M., Cobb, K.M., Esper, J., Goosse, H., Graham, N., Jansen, E., Kiefer, T., Kull, C., Küttel, M., Mosley-Thompson, E., Overpeck, J.T., Riedwyl, N., Schulz, Z., Tudhope, A.W., Villalba, R., Wanner, H., Wolff, E., Xoplaki, E., 2009. High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects. *The Holocene* 19, 3–49.
- Jorissen, F.J., 1987. The distribution of benthic foraminifera in the Adriatic Sea. *Marine Micropaleontology* 12, 21–48.
- Jorissen, F.J., Barmawidjaja, D.M., Puskaric, S., van der Zwaan, G.J., 1992. Vertical distribution of benthic foraminifera in the northern Adriatic Sea: The relation with the organic flux. *Marine Micropaleontology* 19, 131–146.
- King, B., McAllister, F., Wolanski, E., Done, T., Spagnol, S., 2001. River plume dynamics in the centre Great Barrier Reef. In: Wolanski, E. (Ed.), *Oceanographic Processes of Coral Reefs: Physical and Biological links in the Great Barrier Reef*. CRC Press, Boca Raton, pp. 145–160.
- Krull, E., Haynes, D., Lamontagne, S., Gell, P., McKirdy, D., Hancock, G., McGowan, J., Smernik, R., 2009. Changes in the chemistry of sedimentary organic matter within the Coorong over space and time. *Biogeochemistry* 92, 9–25.
- Lamb, A.L., Wilson, G.P., Leng, M.J., 2006. A review of coastal palaeoclimate and relative sea-level reconstructions using  $\delta^{13}\text{C}$  and C/N ratios in organic material. *Earth-Science Reviews* 75, 29–57.
- Langer, M.R., Lipps, J.H., 2003. Foraminiferal distribution and diversity, Madang Reef and Lagoon, Papua New Guinea. *Coral Reefs* 22, 143–154.
- Larcombe, P., Wolfe, K.J., 1999. Terrigenous sediments as influences upon Holocene nearshore coral reefs, central Great Barrier Reef, Australia. *Australian Journal of Earth Sciences* 46, 141–154.
- Lewis, S., Brodie, J., Ledee, E., Alewijnse, M., 2006. The spatial extent of delivery of terrestrial materials from the Burdekin region in the Great Barrier Reef Lagoon. Report 06/02. Australian Centre for Tropical Freshwater Research (ACTFR), James Cook University, Townsville, p. 76.
- Lewis, S.E., Shields, G.A., Kamber, B.S., Lough, J.M., 2007. A multi-trace element coral record of land-use changes in the Burdekin River catchment, NE Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 246, 471–487.
- Loeblich, A.R., Tappan, H., 1994. Foraminifera of the Sahul Shelf and Timor Sea. Cushman Foundation for Foraminiferal Research, Special Publication, p. 661.
- Lybolt, M., Neil, D., Zhao, J.-x., Feng, Y.-x., Yu, K.-F., Pandolfi, J.M., 2011. The shift from natural to human-dominated seascapes: a history of instability in marginal coral reefs. *Frontiers in Ecology and the Environment* 9, 154–160.
- Mantel, N., 1967. Assumption-free estimators using U statistics and a relationship to the jackknife method. *Biometrics* 23, 567–571.
- McArdle, B.H., Anderson, M.J., 2001. Fitting multivariate models to community data: A comment on distance-based redundancy analysis. *Ecology* 82, 290–297.
- McCulloch, M., Fallon, S., Wyndham, T., Hendy, E., Lough, J., Barnes, D., 2003a. Coral record of increased sediment flux to the inner Great Barrier Reef since European settlement. *Nature* 421, 727–730.
- McCulloch, M., Pailles, C., Moody, P., Martin, C.E., 2003b. Tracing the source of sediment and phosphorus into the Great Barrier Reef lagoon. *Earth and Planetary Science Letters* 210, 249–258.
- Merchant, A., Peuke, A.D., Keitel, C., Macfarlane, C., Warren, C.R., Adams, M.A., 2010. Phloem sap and leaf  $\delta^{13}\text{C}$ , carbohydrates, and amino acid concentrations in *Eucalyptus globulus* change systematically according to flooding and water deficit treatment. *Journal of Experimental Botany* 61, 1785–1793.
- Meyers, P.A., 1994. Preservation of elemental and isotopic source identification of sedimentary organic matter. *Chemical Geology* 114, 289–302.
- Murray, J.W., 1991. *Ecology and Palaeoecology of Benthic Foraminifera*. Longman Scientific & Technical, New York, p. 408.
- Murray, J.W., 2006. *Ecology and Applications of Benthic Foraminifera*. Cambridge University Press, Melbourne, p. 438.
- Narayan, Y.R., Pandolfi, J.M., 2010. Benthic foraminiferal assemblages from Moreton Bay, South-East Queensland, Australia: Applications in monitoring water and substrate quality in subtropical estuarine environments. *Marine Pollution Bulletin* 60, 2062–2078.
- Neil, D.T., Orpin, A.R., Ridd, E.V., Yu, B.F., 2002. Sediment yield and impacts from river catchments to the Great Barrier Reef lagoon. *Marine and Freshwater Research* 53, 733–752.
- Oldfield, F., Asioli, A., Accorsi, C.A., Mercuri, A.M., Juggins, S., Langone, L., Rolph, T., Trincardi, F., Wolff, G., Gibbs, Z., Vigliotti, L., Frignani, M., van der Post, K., Branch, N., 2003. A high resolution late Holocene palaeo environmental record from the central Adriatic Sea. *Quaternary Science Reviews* 22, 319–342.
- O'Leary, M.H., 1988. Carbon isotopes in photosynthesis. *Bioscience* 38, 328–336.
- Pandolfi, J.M., 1996. Limited membership in Pleistocene reef coral assemblages from the Huon Peninsula, Papua New Guinea: constancy during global change. *Paleobiology* 22, 152–176.
- Prahl, F.G., Bennett, J.T., Carpenter, R., 1980. The early diagenesis of aliphatic hydrocarbons and organic matter in sedimentary particulates from Dabob Bay, Washington. *Geochimica et Cosmochimica Acta* 44, 1967–1976.

- Pringle, C.M., 2001. Hydrologic connectivity and the management of biological reserves: A global perspective. *Ecological Applications* 11, 981–998.
- Reid, G.C., 1997. Solar forcing of global climate change since the mid-17th century. *Climatic Change* 37, 391–405.
- Renema, W., Troelstra, S.R., 2001. Larger foraminifera distribution on a mesotrophic carbonate shelf in SW Sulawesi (Indonesia). *Palaeogeography, Palaeoclimatology, Palaeoecology* 175, 125–146.
- Reymond, C.E., Bode, M., Renema, W., Pandolfi, M.P., 2011. Ecological incumbency impedes stochastic community assembly in Holocene foraminifera from the Huon Peninsula, Papua New Guinea. *Paleobiology* 37, 670–685.
- Roff, G., 2010. Historical ecology of coral communities from the inshore Great Barrier Reef. PhD thesis, The University of Queensland. UQ eSpace. pp. 138.
- Roff, G., Clark, T., Reymond, C.E., Zhao, J.X., McCook, L., Done, T., Pandolfi, J.M., 2012. Palaeoecological evidence of a historical collapse of corals at Pelorus Island, inshore Great Barrier Reef, following European settlement. *Proceedings of the Royal Society of London - Series B: Biological Sciences* <http://dx.doi.org/10.1098/rspb.2012.2100>.
- Rullkötter, J., 2006. Organic matter: The driving force for early diagenesis. In: Schulz, H., Zabel, M. (Eds.), *Marine Geochemistry*. Springer, Berlin, pp. 125–168.
- Sackett, W.M., Thompson, R.R., 1963. Isotopic organic carbon composition of recent continental derived clastic sediments of Eastern Gulf Coast, Gulf of Mexico. *Bulletin of the American Association of Petroleum Geologists* 47, 525–528.
- Sandini, S.A., Smith, J.E., DeMartini, E.E., Dinsdale, E.A., Donner, S.D., Friedlander, A.M., Konotchick, T., Malay, M., Maragos, J.E., Obura, D., Pantos, O., Paulay, G., Richie, M., Rohwer, F., Schroeder, R.E., Walsh, S., Jackson, J.B.C., Knowlton, N., Sala, E., 2008. Baselines and degradation of coral reefs in the northern Line Islands. *PLoS One* 3, e1548.
- Schueth, J.D., Frank, T.D., 2008. Reef foraminifera as bioindicators of coral reef health: Low Isles Reef, northern Great Barrier Reef, Australia. *Journal of Foraminiferal Research* 38, 11–22.
- Schwartz, D., Mariotti, A., Lanfranchi, R., Guillet, B., 1986.  $^{13}\text{C}/^{12}\text{C}$  Ratios of soil organic matter as indicators of vegetation changes in the Congo. *Geoderma* 39, 97–103.
- Sen Gupta, B.K., 1999. *Modern Foraminifera*. Kluwer Academic Publishers, London, p. 384.
- Sen Gupta, B.K., Aharon, P., 1994. Benthic foraminifera of bathyal hydrocarbon vents of the Gulf of Mexico: Initial report on communities and stable isotopes. *Geo-Marine Letters* 14, 88–96.
- Shultz, D.J., Calder, J.A., 1976. Organic carbon  $^{13}\text{C}/^{12}\text{C}$  variations in estuarine sediments. *Geochimica et Cosmochimica Acta* 40, 381–385.
- Siegel, B.Z., Siegel, S.M., 1973. The chemical composition of algal cell walls. *Critical Reviews in Microbiology* 3, 1–26.
- Smith, S.V., Ibarra-Obando, S.E., Diaz-Castaneda, V., Aranda-Manteca, F.J., Carriquiry, J.D., Popp, B.N., Gonzalez-Yajimovich, O., 2008. Sediment organic carbon in Todos Santos Bay, Baja California, Mexico. *Estuaries and Coasts* 31, 719–727.
- Sokal, R.R., Rohlf, F.J., 1995. *Biometry: The principles and practice of statistics in biological research*, 3rd ed. Freeman and Co., New York, p. 887.
- Somerfield, P.J., Clarke, K.R., 1995. Taxonomic levels, in marine community studies, revisited. *Marine Ecology Progress Series* 127, 113–119.
- Somerfield, P.J., Clarke, K.R., Olsford, F., 2002. A comparison of the power of categorical and correlational tests applied to community ecology data from gradient studies. *Journal of Animal Ecology* 71, 581–593.
- Tager, D., Webster, J.M., Potts, D.C., Renema, W., Braga, J.C., Pandolfi, J.M., 2010. Community dynamics of Pleistocene coral reefs during alternative climatic regimes. *Ecology* 91, 191–200.
- Thibodeau, B., de Vernal, A., Mucci, A., 2006. Recent eutrophication and consequent hypoxia in the bottom waters of the Lower St. Lawrence Estuary: Micropaleontological and geochemical evidence. *Marine Geology* 231, 37–50.
- Torgersen, T., Chivas, A.R., 1985. Terrestrial organic carbon in marine sediment: a preliminary balance for a mangrove environment derived from  $^{13}\text{C}$ . *Chemical Geology* 52, 379–390.
- Torgersen, T., Chivas, A.R., Chapman, A., 1983. Chemical and isotopic characterisation and sedimentation rates in Princess Charlotte Bay, Queensland. *AGSO Journal of Australian Geology and Geophysics* 8, 191–200.
- Tsujimoto, A., Yasuhara, M., Nomura, R., Yamazaki, H., Sampei, Y., Hirose, K., Yoshikawa, S., 2008. Development of modern benthic ecosystems in eutrophic coastal oceans: The foraminiferal record over the last 200 years, Osaka Bay, Japan. *Marine Micropaleontology* 69, 225–239.
- Uthicke, S., Nobes, K., 2008. Benthic Foraminifera as ecological indicators for water quality on the Great Barrier Reef. *Estuarine, Coastal and Shelf Science* 78, 763–773.
- Uthicke, S., Thompson, A., Schaffelke, B., 2010. Effectiveness of benthic foraminiferal and coral assemblages as water quality indicators on inshore reefs of the Great Barrier Reef, Australia. *Coral Reefs* 29, 209–225.
- van der Zwaan, G.J., Jorissen, F., 1991. Biofacial patterns in river-induced shelf anoxia. Geological Society, London, Special Publications 58, 65–82.
- van Woesik, R., Done, T.J., 1997. Coral communities and reef growth in the southern Great Barrier Reef. *Coral Reefs* 16, 103–115.
- Wakeham, S., 2002. Diagenesis of organic matter at the water-sediment interface. In: Gianguzza, A., Pelizzetti, E., Sarmantano, S. (Eds.), *Chemistry of Marine Water and Sediments*. Springer, Berlin, pp. 147–164.
- Wilson, G.P., Lamb, A.L., Leng, M.J., Gonzalez, S., Huddart, D., 2005.  $\delta^{13}\text{C}$  and C/N as potential coastal palaeoenvironmental indicators in the Mersey Estuary, UK. *Quaternary Science Reviews* 24, 2015–2029.
- Wollenburg, J.E., Mackensen, A., Kuhnt, W., 2007. Benthic foraminiferal biodiversity response to a changing Arctic palaeoclimate in the last 24,000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology* 255, 195–222.
- Zhao, J.X., Hu, K., Collerson, K.D., Xu, H.K., 2001. Thermal ionization mass spectrometry U-series dating of a hominid site near Nanjing, China. *Geology* 29, 27–30.
- Zhao, J.X., Yu, K.F., Feng, Y.X., 2009. High-precision  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$  disequilibrium dating of the recent past - a review. *Quaternary Geochronology* 4, 423–433.